LEBT and RFQ

John Staples and Qing Ji, LBNL

12 April 2011

Issues

LEBT R&D program

Chopping in LEBT: emittance growth

New RFQ beam dynamics design

RFQ output energy

RFQ cavity for new beam dynamics design

RFQ Cavity engineering

LEBT Configuration and Requirements

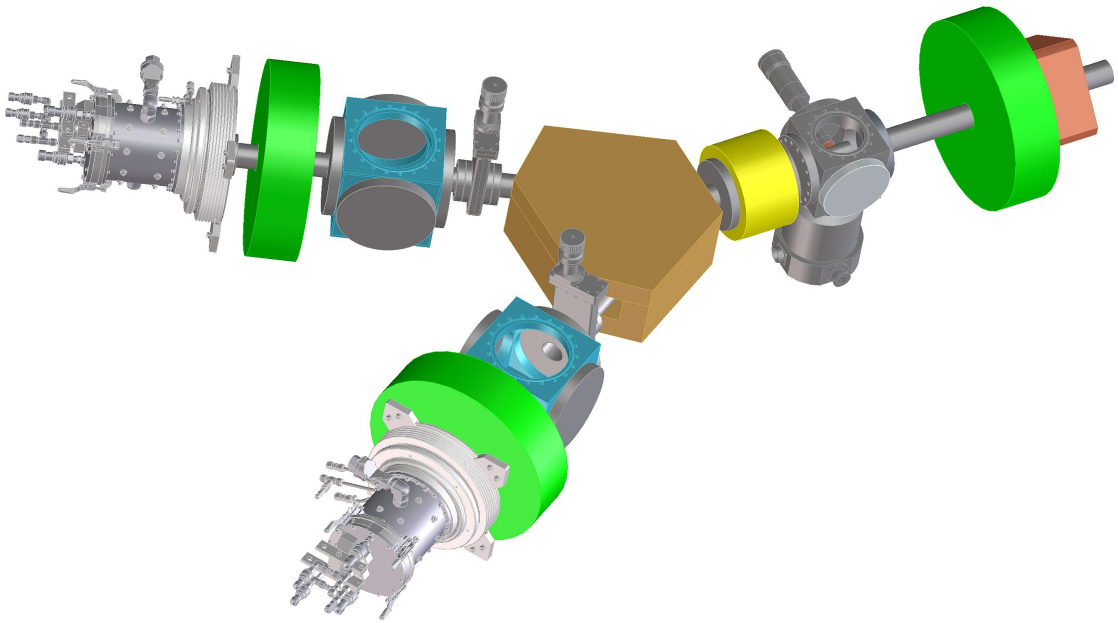
Transport and focus 20 keV beam from ion source to RFQ

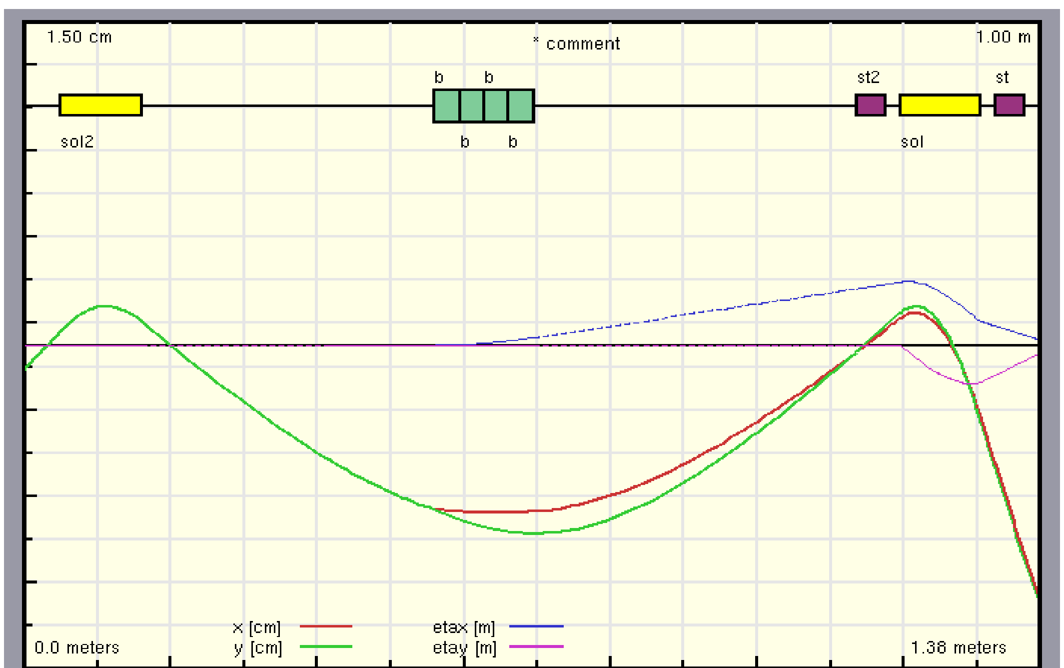
Provide for 2 ion sources for redundancy and quick source change

Include chopper for a 500 microsecond gap in beam for HEBT switch magnet

Diagnostics to tune ion source, steer it into RFQ

Investigate higher frequency chopper scenarios





LEBT Configuration

20 keV

5 mA DC beam

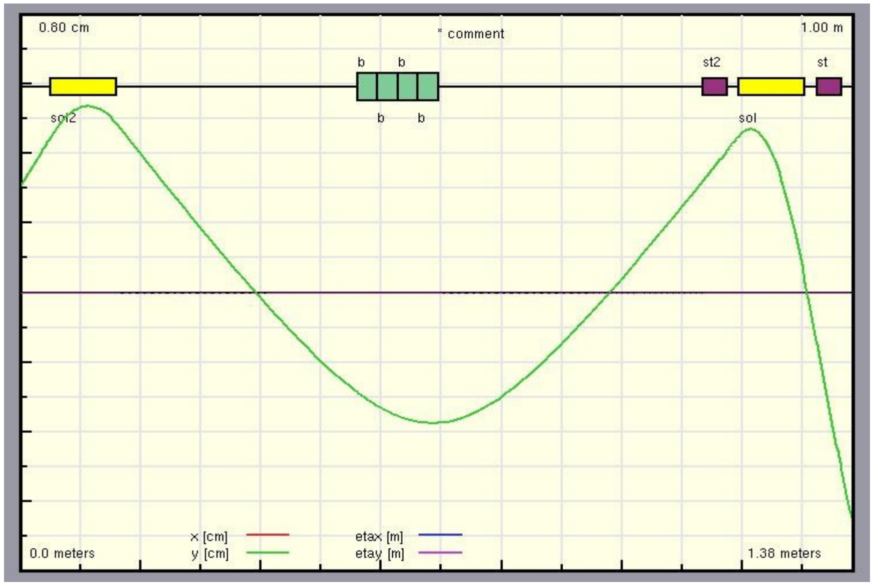
>90% neutralization

2 solenoids

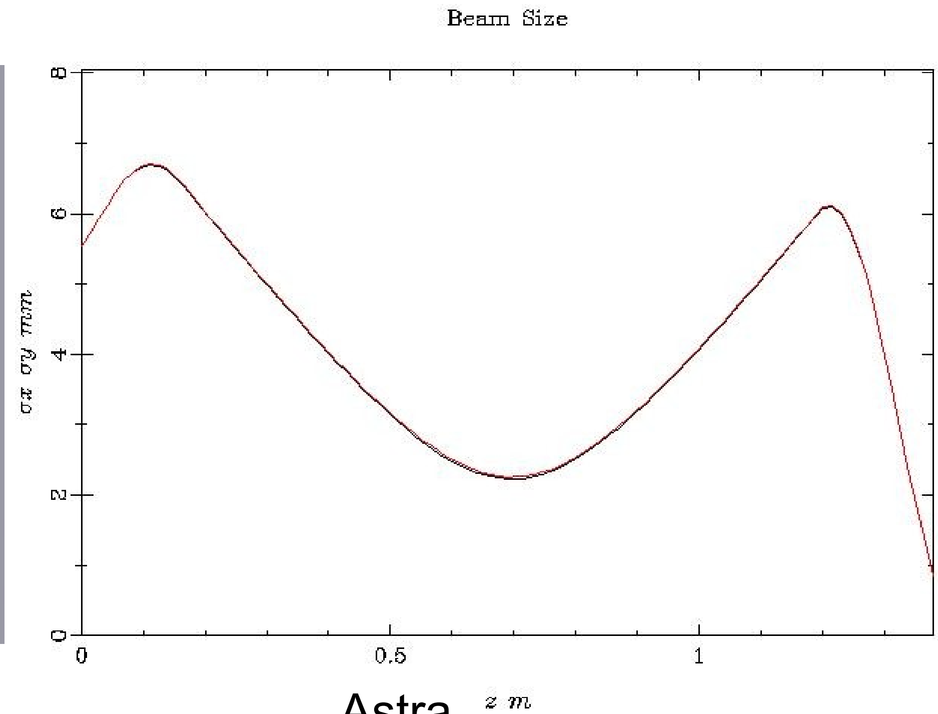
2 ion H-minus ion sources

±20 degree selector magnet
chopper at end

Astra macroparticle simulation of LEBT



TLAT



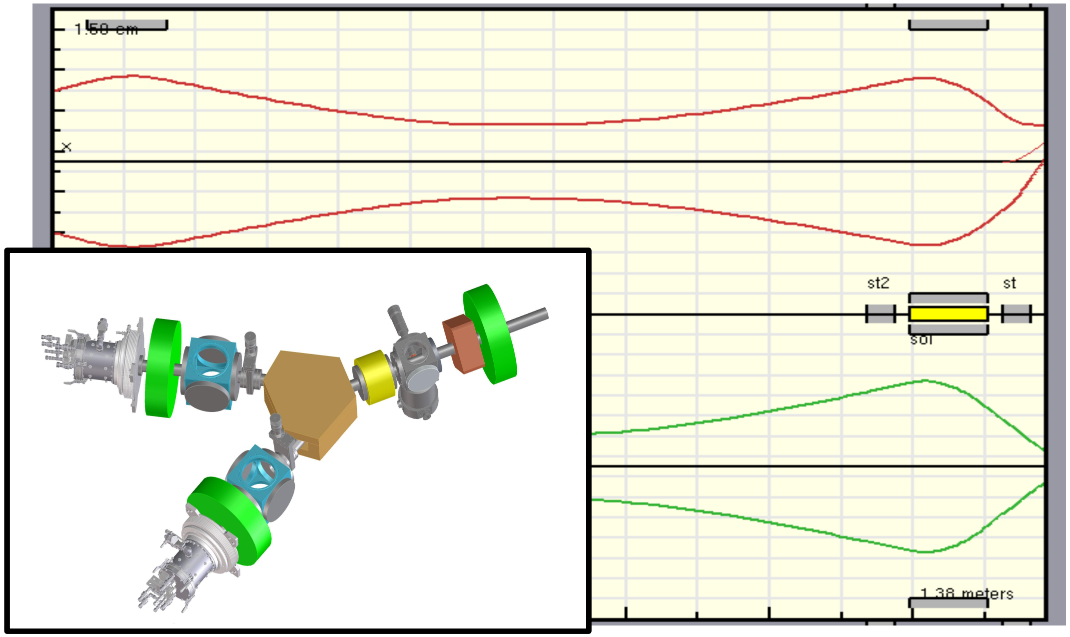
Astra

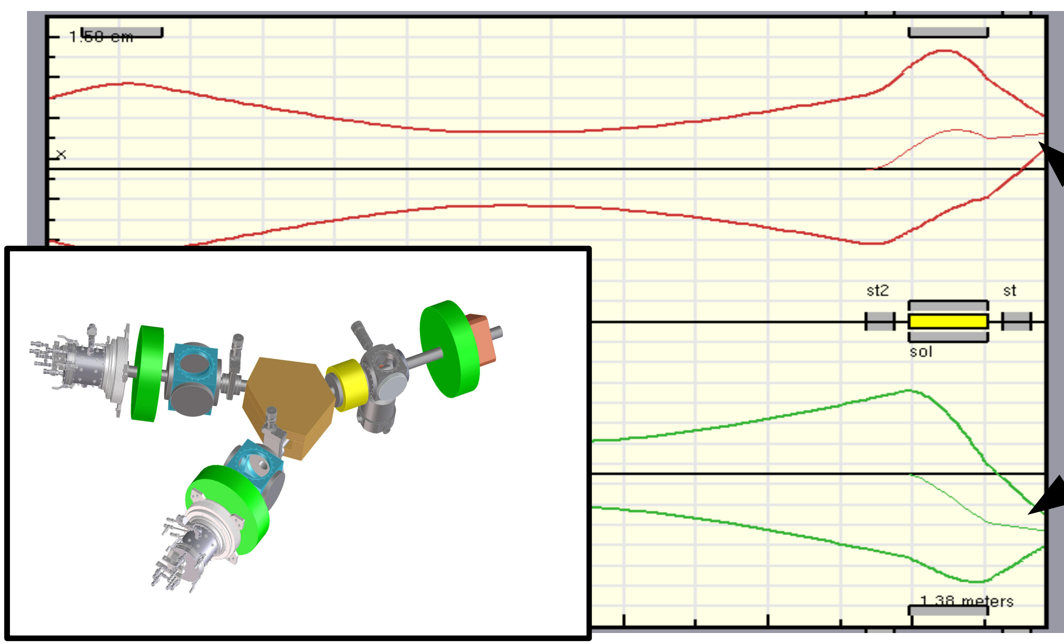
TLAT is based on a TRACE3D physics model.   It is an envelope code that incorporates both 2-D and 3-D space charge, deflectors, steering, etc.

Astra is a workhorse of the electron community. It is a macroparticle code with 3-D PIC space charge.   It works as well with hadrons and offers extensive graphics and analysis facilities. Accept ion source emittance scan and simulate nonlinear effects.

TLAT, Astra, Warp and Trace-3D all in agreement, provide different simulation approaches.

LEBT Chopper Location Choice





20 keV beam. $\beta = 0.0065$

Two locations considered:

In front of last solenoid

After last solenoid

For position in front of last solenid, plate spacing > 2 cm.

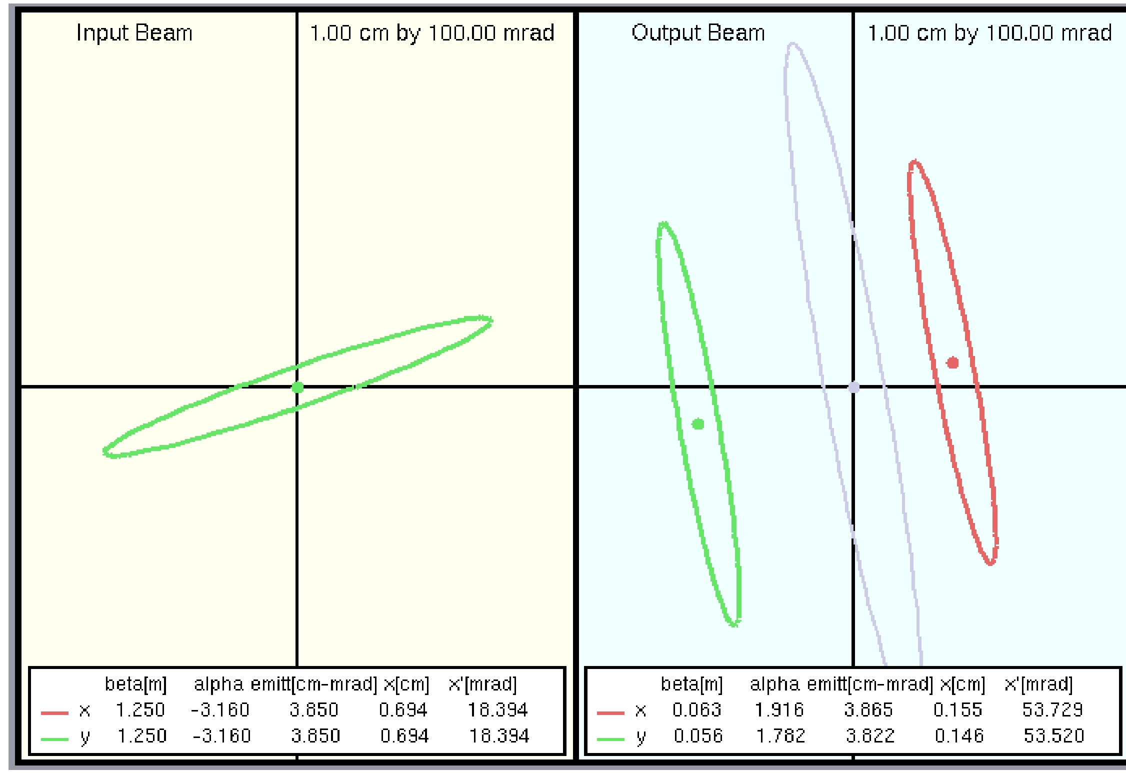
For effective length of 4 cm, transit time is 20 nsec

TW chopper for this beam velocity probably not practical

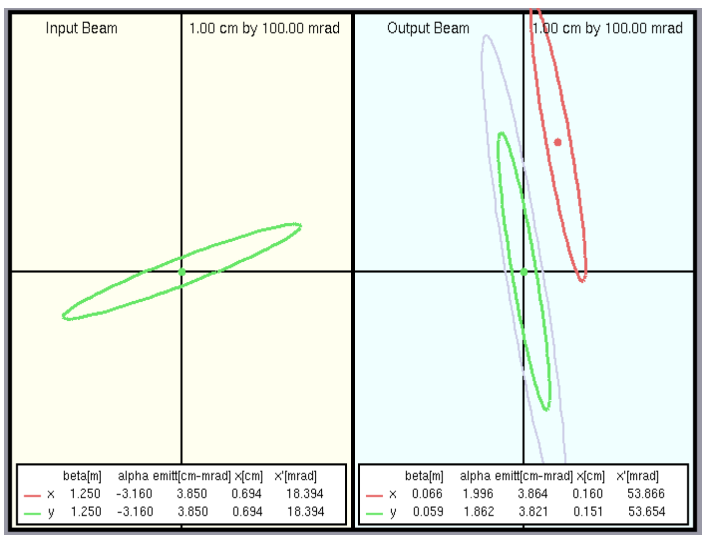
deflection at RFQ entrance from electrodes preceeding solenoid

LEBT Chopper displacement of x and y phase spaces at RFQ Entrance

Chopping ahead of last solenoid in x-direction displaces both x and y ellipses.



Gray ellipse is RFQ acceptance ellipse orientation.



Phase space for post-solenoid chop.

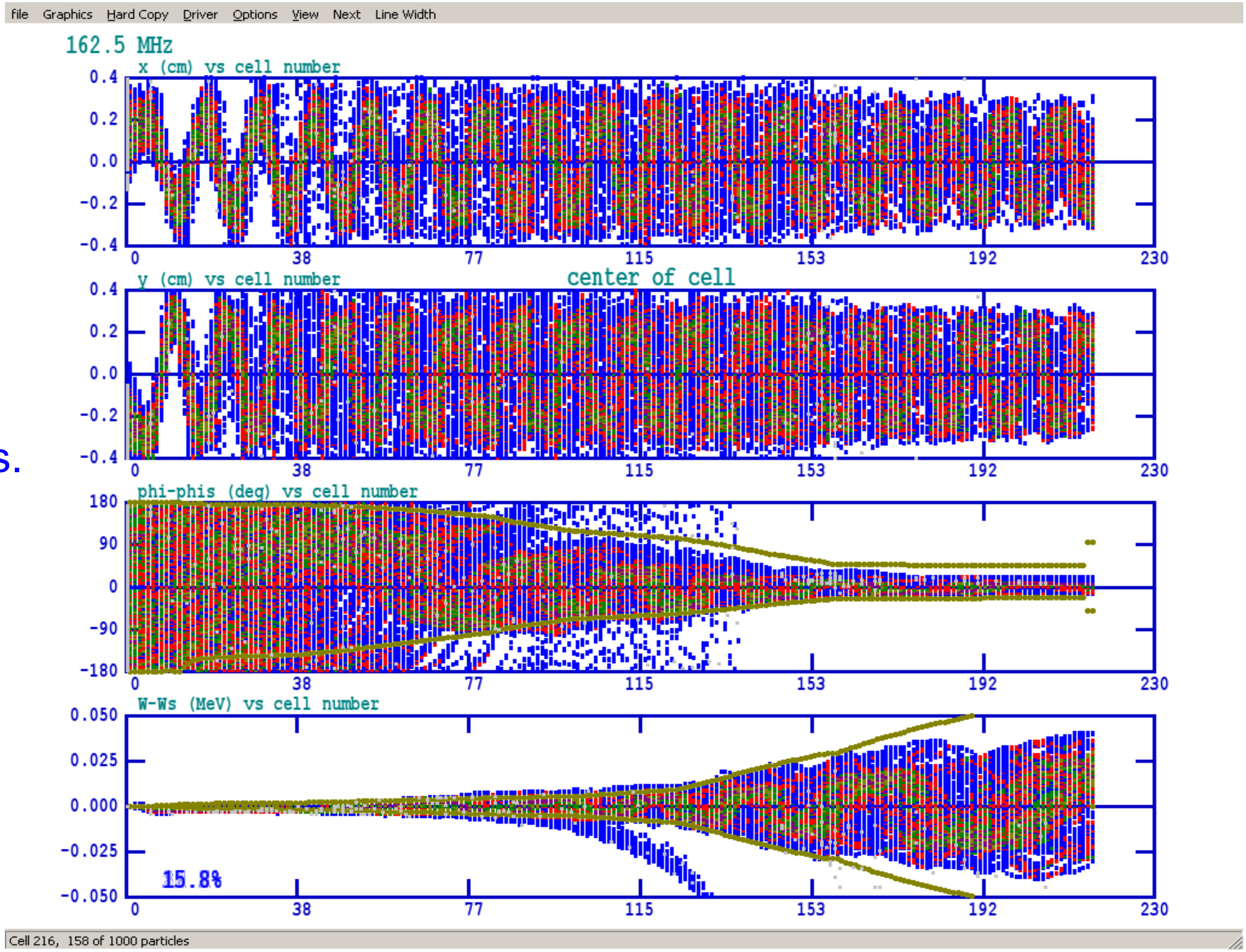
RFQ transmission and output beam characteristics simulated with various chopper deflection field strengths to determine RFQ transmission and effect on RFQ output beam.

Response of RFQ to displaced entrance beam

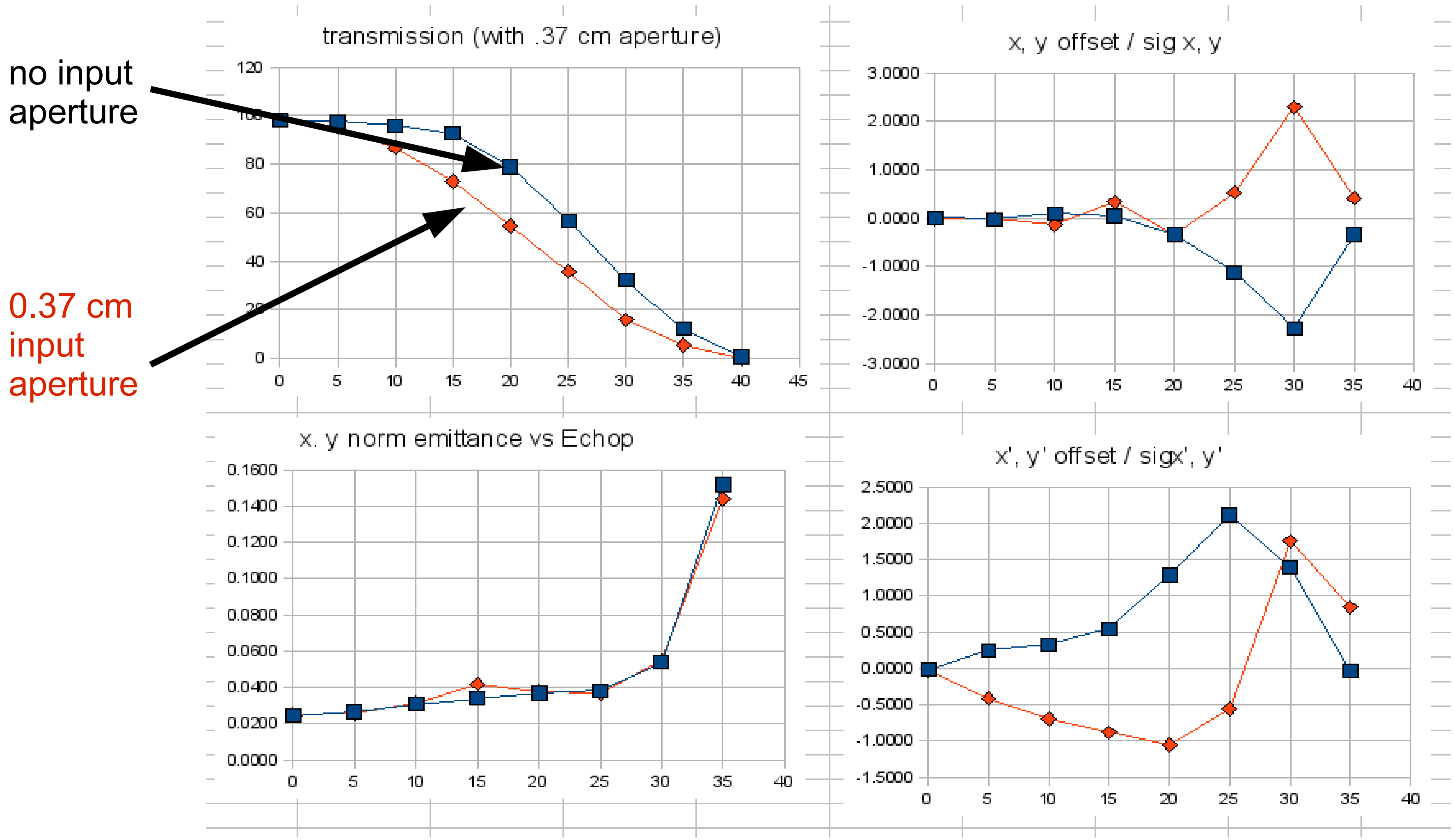
Beam injected into the RFQ off-axis will emerge from the RFQ with strong coherent betatron motion.

Transverse beam undergoes about 17 betatron oscillations.

Output beam offset very dependent on gradient, as number of phase oscillations changes.



RFQ exit beam parameters vs. LEBT chopper gradient



Horizontal axis: transverse chopper field, kV/m for 4 cm long deflector upstream of solenoid.

Details highly dependent on gradient (tune). Input aperture doesn't help much.

Therefore, 20 MHz chopping in LEBT looks difficult.

Challenges of LEBT Chopping

Off-axis beam at RFQ entrance is reproduced as off-axis beam at RFQ exit

Beam aperture at RFQ entrance is not effective in removing off-axis beam

Don't make the RFQ act as a beam collimator by using a very small aperture

Off-axis RFQ input beam must be cleaned up in the MEBT

For 500 microsecond, 10 Hz chop: remove “bad” edges in MEBT

For possible ca. 1 MHz LEBT chop: MEBT chopper should still apply

Faster LEBT chop: most beam will be off-axis and/or satellite bunches:
just use MEBT chopping

LBNL LEBT chopper: two scenarios:
before solenoid more effective and should be tested
after solenoid but with higher deflection voltage

The H-minus neutralizing plasma includes both positive ions and electrons, due to different production and loss rates, and they have different mobilities. Chopping should be as close to the RFQ as possible. Upstream LEBT transport is neutralized.

LEBT R&D Program

The LEBT to be developed and tested incrementally

Extraction and 20 keV acceleration from the ion source
Electron diversion and trapping
Ion source emittance measurements
Chopper implementation at RFQ entrance
Establish matching parameters required by RFQ
Emittance, neutralization time measurements of chopped beam

The separation of the 20 keV acceleration, the magnetic transport, and the pulsed electric field chopper will ensure high reliability.

RFQ

New RFQ Beam Dynamics Design

The injection energy is lowered to 20 keV, reducing the longitudinal emittance

The vane-vane voltage is lowered to reduce cavity power

The aperture is reduced to maintain the transverse focusing phase advance

The capture of beam into a low-emittance output is 98%

New Version

2a: 2.1 MeV
2b: 2.5 MeV

Lower injection energy

Higher capture

Lower power requirement

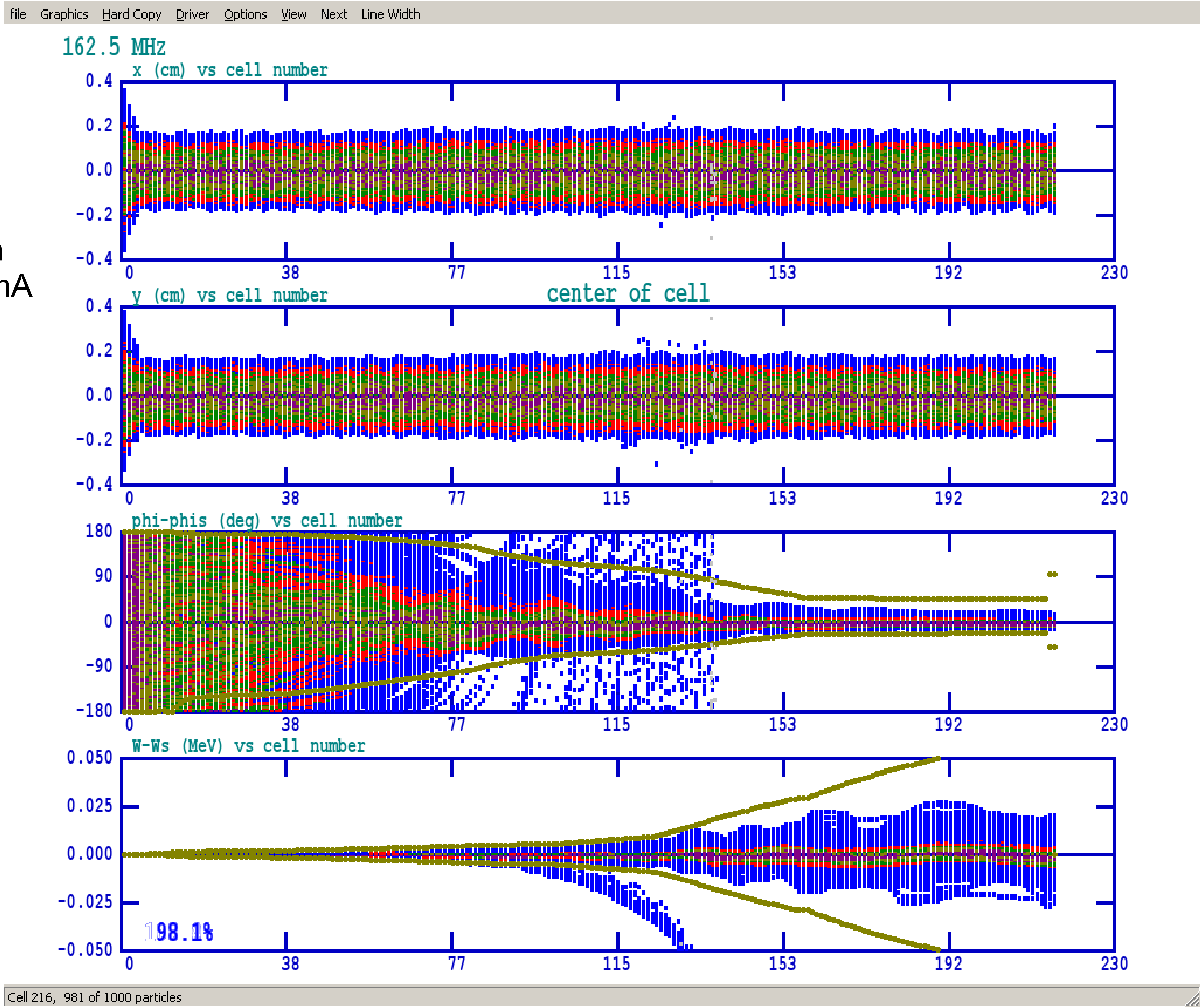
Lower surface field

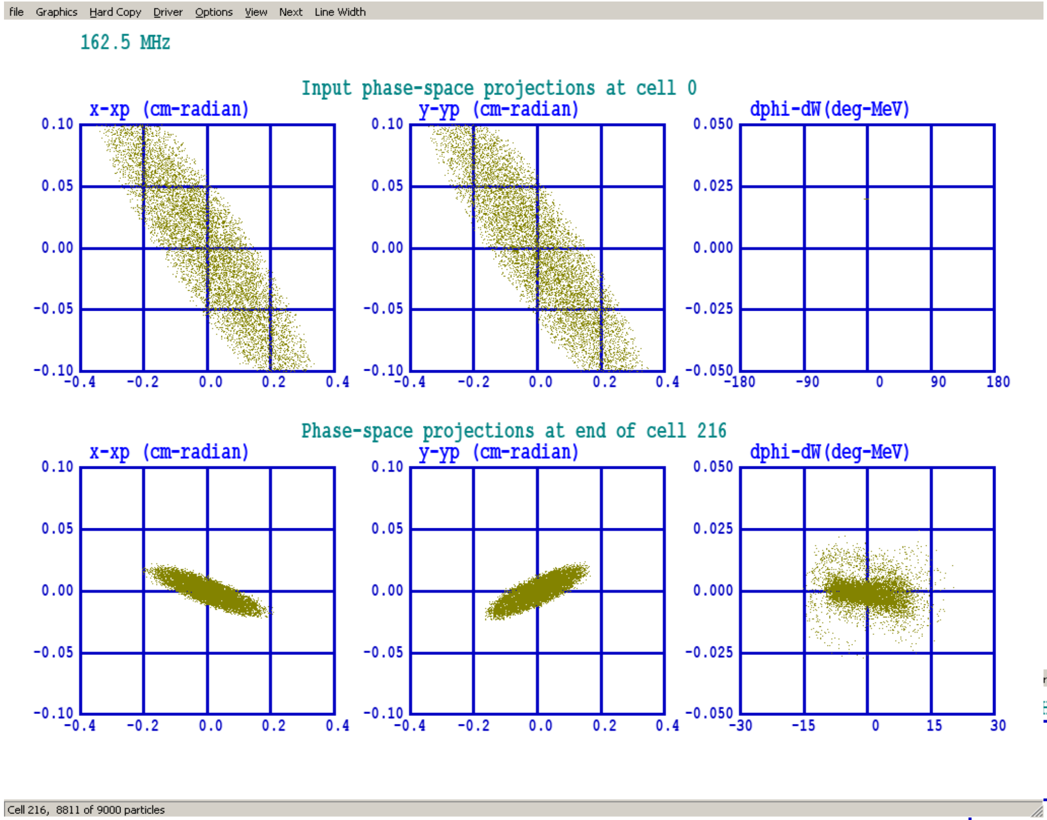
Lower output emittance

2.1 and 2.5 MeV options

	V1	V2a	V2b		
Duty Factor	100	100		percent	
Input Energy	35	20		keV	
Output Energy	2.5	2.1	2.5	MeV	
Length	384	404	489	cm	length of vanes
V_{vv}	90.8	68		kV	intervane voltage
N_{cells}	135	212	228		
Input current	5	5		mA	
Transmission	93.7	97.8		percent	
Transverse Loss		0.05		percent	transverse beam loss on vanes
Longitudinal Loss		2.2		percent	beam out of bucket
B	9.0	9.0			focusing parameter
P'/cm	402	180.3		watts/cm	copper power per linear RFQ length
P_{copper}	154	73	88	kW	Superfish power, 100% Q_0, no ends
P_{beam}	12.5	10.5	12.5	kW	beam power
P_d	2.05	0.90		W/cm^2	max wall power density
L/λ	2.1	2.2	2.6		length/free-space wavelength
E_{max}	20.8	16.4		MV/m	peak vanetip field
kilp	1.53	1.21		kilpatrick	peak vanetip field
r_0	0.605	0.521		cm	average vane tip dist from axis
$r_{long,\ min}$	1.18	1.87		cm	minimum long radius of curvature
r_{transv}	0.605	0.391		cm	vane tip transverse radius
a_{min}	0.395	0.316		cm	minimum aperture
cavity radius		17.5		cm	max outer cavity wall dimension
$\epsilon_{x,y\ in}$	0.0250	0.0250		cm-mrad	normalized transverse input emittance
$\epsilon_{x,y}$	0.029	0.0254		cm-mrad	normalized transv output emittance
ϵ_z	0.0279	0.0158	0.0172	cm-mrad	normalized longitudinal emittance
ϵ_z	51.1	28.9	31.5	keV-deg	longitudinal output emittance
ϵ_z	0.88	0.49	0.54	keV-nsec	longitudinal output emittance

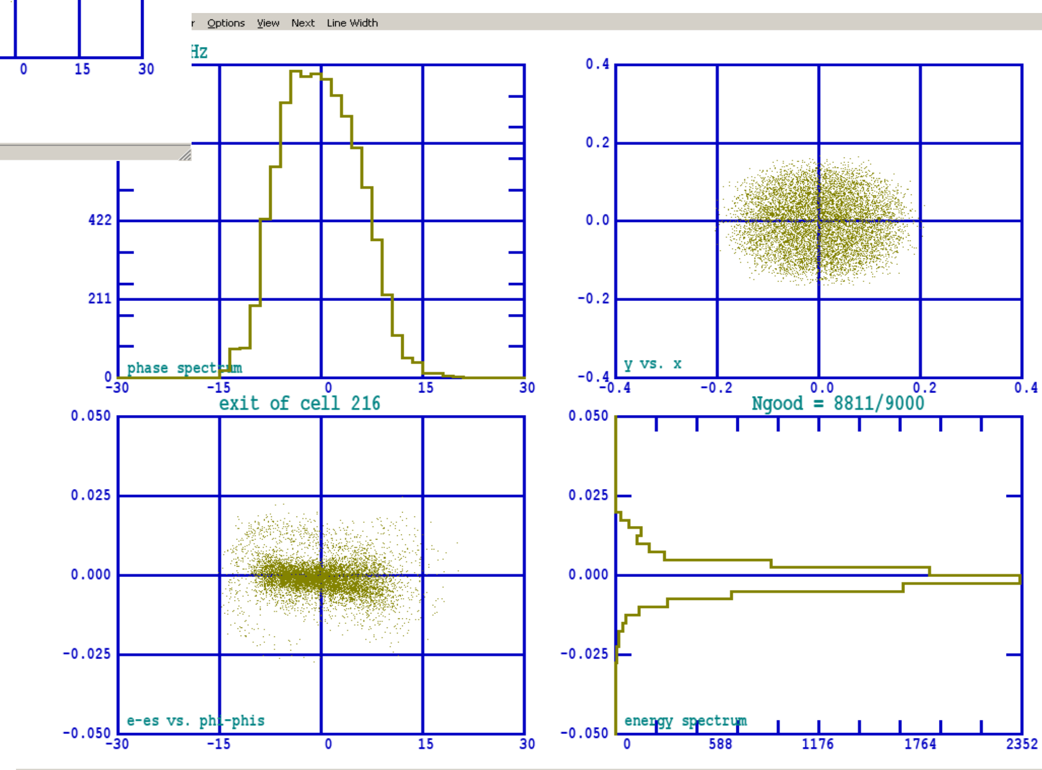
Parmteqm run for 5 mA





Longitudinal output phase space and distributions.

Longitudinal emittance 0.50 keV-nsec and shows little filamenting structure



Transverse phase space at entrance and exit (same scales).

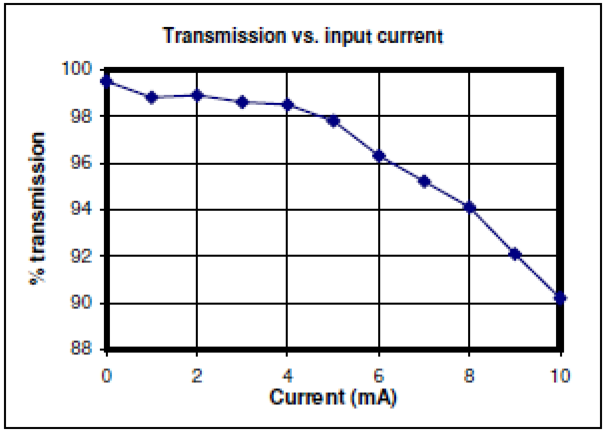
Waterbag input beam distribution, 0.25 pi mm-mrad rms emittance

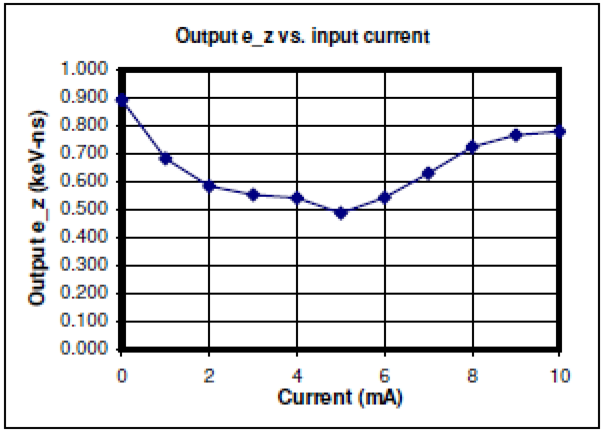
RFQ beam parameter dependence (Qing Ji)

Transmission and output emittance vs. current and input emittance.
RFQ design optimized for 5 mA, 0.25 pi mm-mrad input emittance.

Response of RFQ 23Feb11

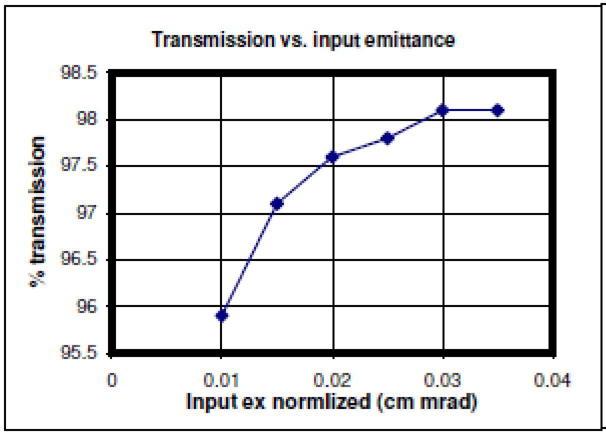
I (mA)	Transm. (%)	e_z (cm-mrad)	e_z (keV-ns)
0	99.5	0.02857	0.890
1	98.8	0.02185	0.681
2	98.9	0.01869	0.582
3	98.6	0.01769	0.551
4	98.5	0.01733	0.540
5	97.8	0.01559	0.486
6	96.3	0.01736	0.541
7	95.2	0.02016	0.628
8	94.1	0.02318	0.722
9	92.1	0.02454	0.765
10	90.2	0.02496	0.778

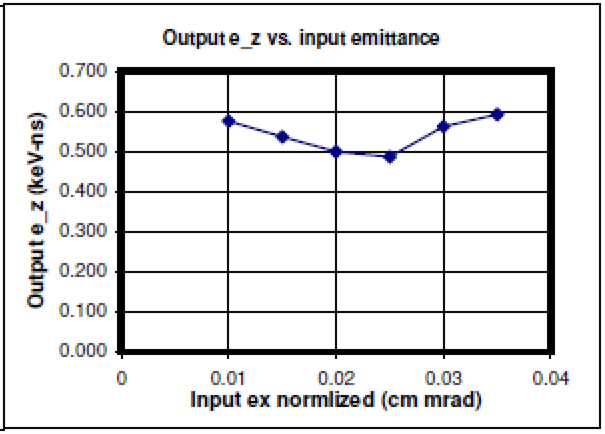




Response to input emittance, current - 5mA

n (cm m	Transm. (%)	e_z (cm-mrad)	e_z (keV-ns)
0.01	95.9	0.01846	0.575
0.015	97.1	0.01719	0.536
0.02	97.6	0.01601	0.499
0.025	97.8	0.01559	0.486
0.03	98.1	0.01802	0.562
0.035	98.1	0.01899	0.592



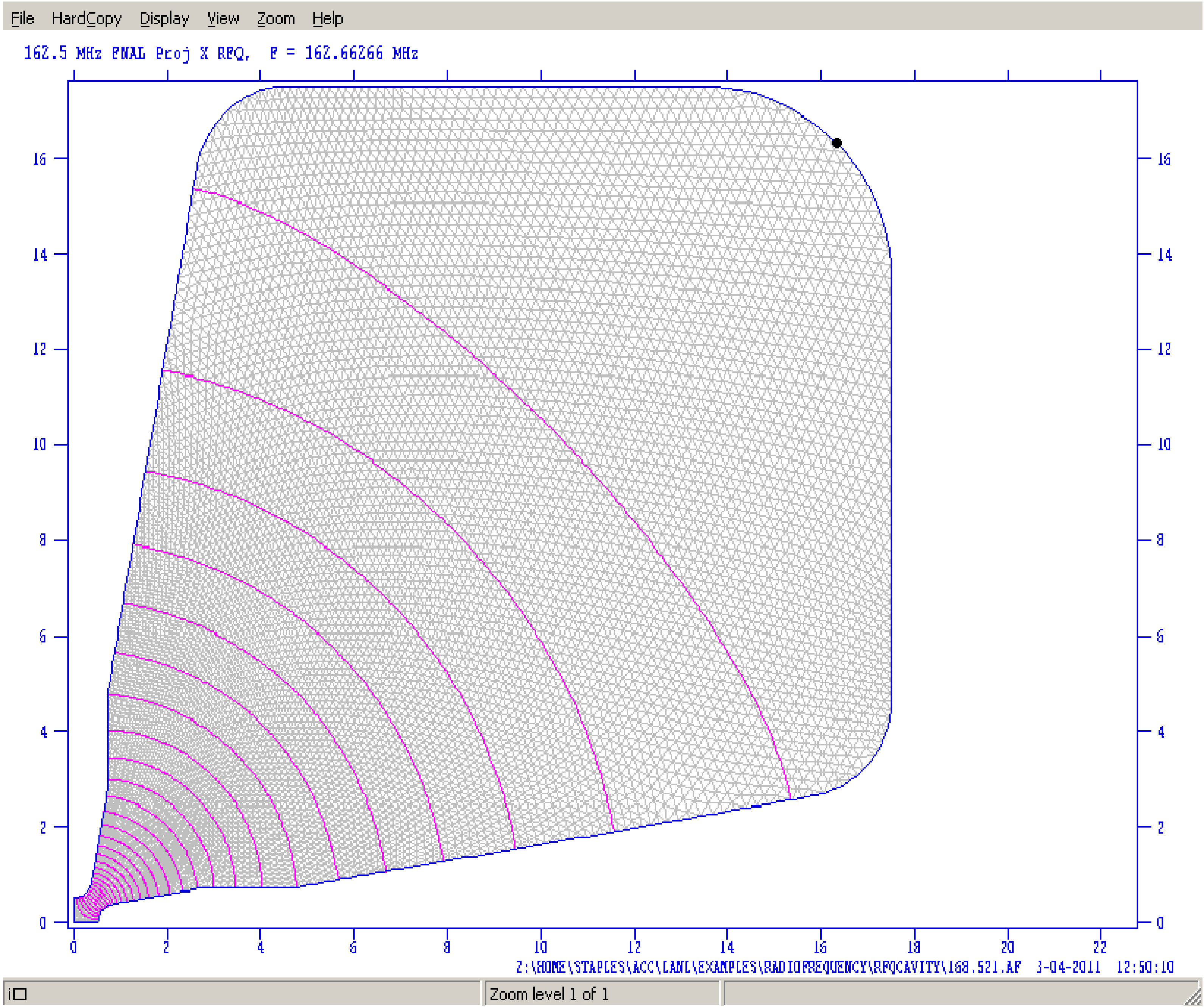


RFQ cavity reshaped for new geometry near vane tips.

r_{transv} = 0.75 r_0 lowers vane-tip capacitance

68 kV between vane tips

Minimum longitudinal radius 1.87 cm for robust form cutter



Wall power density < 1 W/cm^2

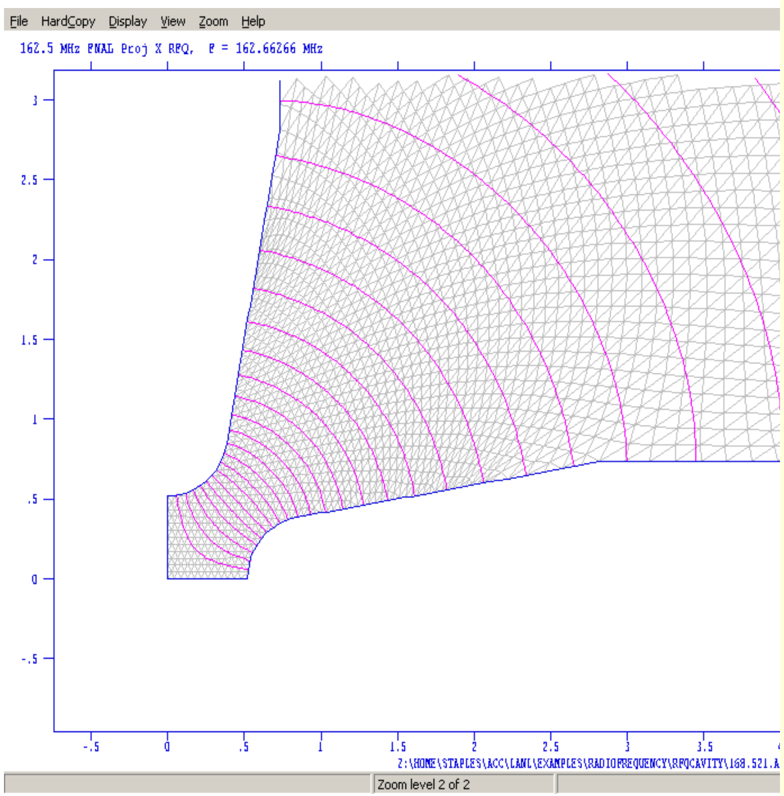
180 watts / cm cavity length

1.2 kilpatrick peak field

```
Superfish output summary for problem description:
162.5 MHz FNAL Proj X RFQ.
Problem file: Z:\HOME\STAPLES\ACC\LANL\EXAMPLES\RADIOFREQUENCY\RFQCAVITY\168.521.AF   3-04-2011
---------------------------------------------------------------------------------
All calculated values below refer to the mesh geometry only.
Field normalization (NORM = 0):     EZERO =      6.52591 MV/m
Frequency                                 =    162.66266 MHz
Normalization factor for E0 =  6.526 MV/m =     8679.912
Stored energy                             =  7.28645E-04 Joules/cm
Using standard room-temperature copper.
Surface resistance                        =      3.32740 milliOhm
Normal-conductor resistivity              =      1.72410 microOhm-cm
Operating temperature                     =      20.0000 C
Power dissipation                         =      44.6260 W/cm
Q    =   16687.7          Shunt impedance =     4972.012 MOhm/m
r/Q  =    36.449 Ohm   Wake loss parameter =      0.00931 V/pC
Average magnetic field on the outer wall  =      2270.39 A/m, 857.583 mW/cm^2
Maximum H (at X,Y = 16.3284,16.3284)      =      2304.06 A/m, 883.205 mW/cm^2
Maximum E (at X,Y = 0.625753,0.265591)    =      16.3531 MV/m, 1.20243 Kilp.
Ratio of peak fields Bmax/Emax            =       0.1771 mT/(MV/m)
Peak-to-average ratio Emax/E0             =       2.5059
```

Wall segments:

Segment	Xend (cm)	Yend (cm)	Emax (MV/m)	Power (W)	P/A (mW/cm^2)	dF/dX (MHz/mm)	dF/dY (MHz/mm)
	0.0000	0.52100					
2	0.25130	0.61250	16.25	1.9979E-03	7.323	1.086	2.805
3	0.38510	0.84410	16.34	1.4960E-02	54.83	2.481	1.557
4	0.60655	2.1000	11.33	0.2652	207.9	1.973	0.3478
5	0.73240	2.8137	3.065	0.2502	345.3	0.2416	4.2605E-02
6	0.73240	4.8137	2.365	0.9360	468.0	0.1857	0.000
7	1.1120	7.0000	0.9187	1.298	584.8	1.9746E-02	3.4287E-03
8	2.1000	12.690	0.6917	4.191	725.7	-0.1143	-1.9840E-02
9	2.6483	15.847	0.2535	2.613	815.2	-0.1037	-1.7999E-02
10	3.3324	17.032	8.4013E-02	1.163	833.4	-4.1406E-02	-2.3946E-02
11	4.6179	17.500	4.5577E-02	1.169	837.8	-1.6474E-02	-4.5298E-02
12	7.0000	17.500	7.2921E-02	2.011	844.3	0.000	-8.4333E-02
13	13.500	17.500	7.7929E-02	5.629	865.9	0.000	-0.2358
14	16.328	16.328	3.8634E-02	2.771	882.1	-4.3581E-02	-0.1051
15	17.500	13.500	3.7971E-02	2.771	882.1	-0.1051	-4.3580E-02
16	17.500	7.0000	7.7507E-02	5.629	866.0	-0.2358	0.000
17	17.500	4.6179	7.2478E-02	2.011	844.4	-8.4332E-02	0.000
18	17.032	3.3324	4.5403E-02	1.169	837.8	-4.5297E-02	-1.6473E-02
19	15.847	2.6483	8.4083E-02	1.163	833.4	-2.3947E-02	-4.1405E-02
20	12.690	2.1000	0.2519	2.613	815.2	-1.7999E-02	-0.1037
21	7.0000	1.1120	0.6918	4.191	725.7	-1.9840E-02	-0.1143
22	4.8137	0.73240	0.9221	1.298	584.8	3.4315E-03	1.9762E-02
23	2.8137	0.73240	2.356	0.9359	468.0	0.000	0.1853
24	2.1000	0.60655	3.070	0.2502	345.2	4.2720E-02	0.2423
25	0.84410	0.38510	11.24	0.2652	207.9	0.3483	1.975
26	0.61250	0.25130	16.35	1.4975E-02	54.88	1.557	2.477
27	0.52100	0.0000	16.24	2.0046E-03	7.348	2.806	1.088
			Total	44.63			

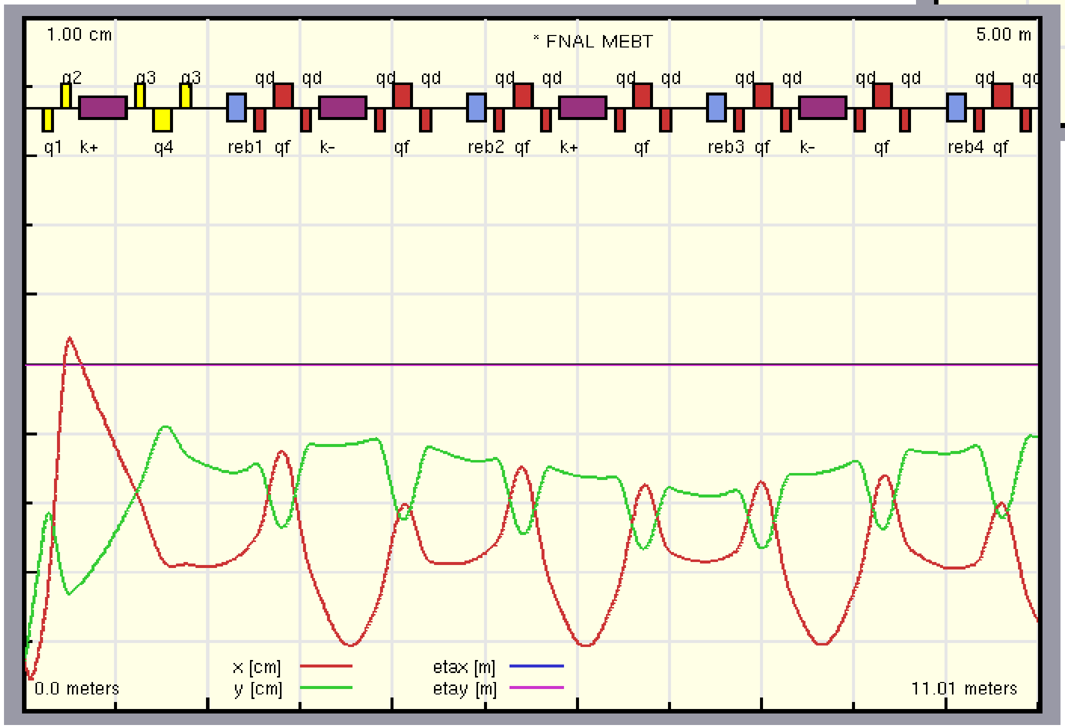


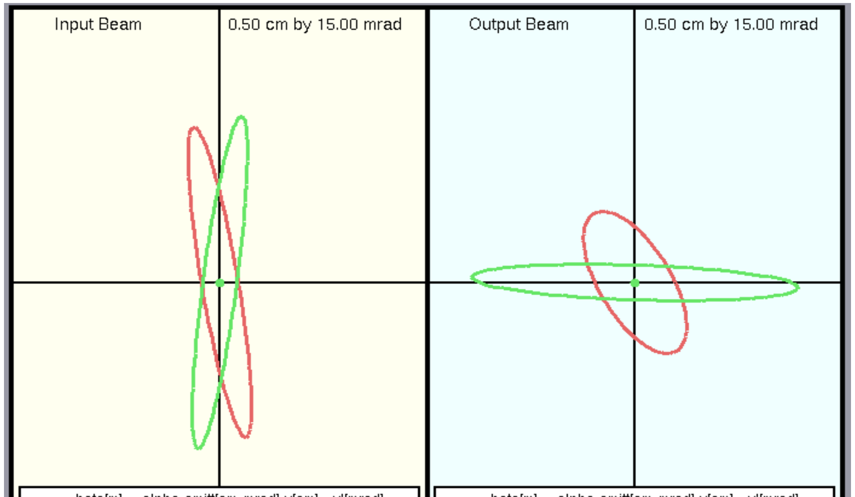
RFQ-MEBT Matching Section For FNAL MEBT Lattice Example

Add doublet and decouple the first triplet.

30 pcoul bunch charge (5 mA)

Works well with new MEBT design





Input Beam:

	beta[m]	alpha	emitt[cm-mrad]	x[cm]	x'[mrad]
x	0.156	1.402	0.377	0.077	8.479
y	0.118	-1.270	0.374	0.066	9.103

Output Beam:

	beta[m]	alpha	emitt[cm-mrad]	x[cm]	x'[mrad]
x	0.410	0.797	0.377	0.124	3.881
y	4.145	0.303	0.374	0.394	0.992

RFQ Structure Engineering

Lessons learned from SNS, ADNS, SNS RFQ Replacement engineering studies

RFQ operates CW, but power densities less than half of SNS RFQ at 6% DF.

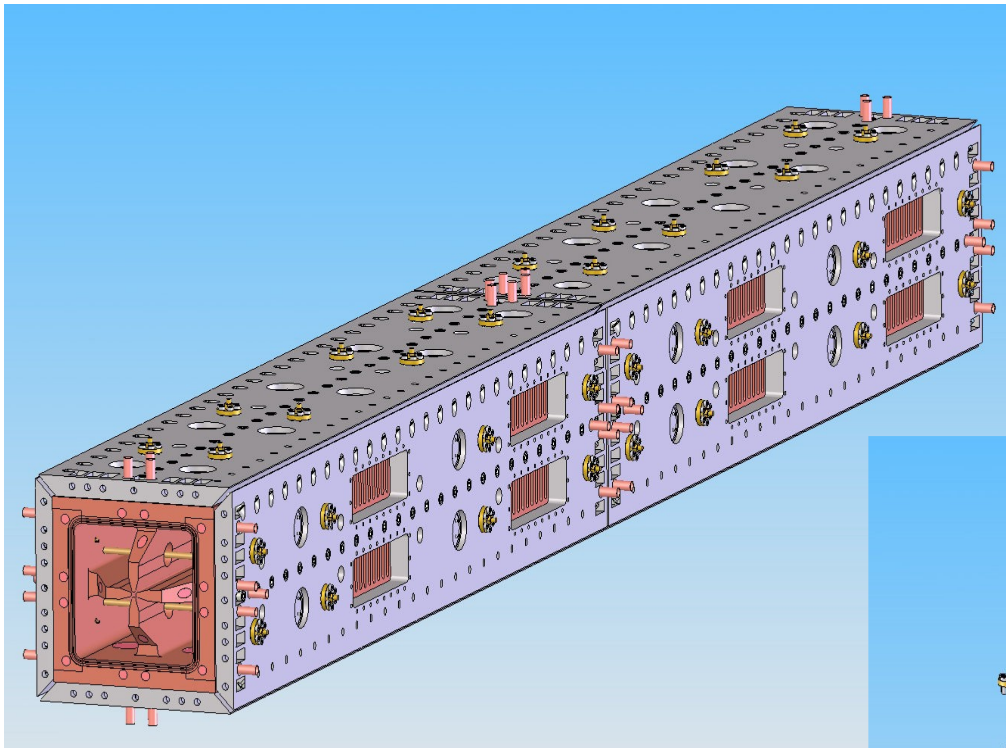
Peak fields about 1.2 kilpatrick

Relatively small length to free-space wavelength may allow no stabilization (TBD).

Will model structure electrodynamics with MWS, do an extensive error analysis to determine need for stabilization, assembly error tolerances.

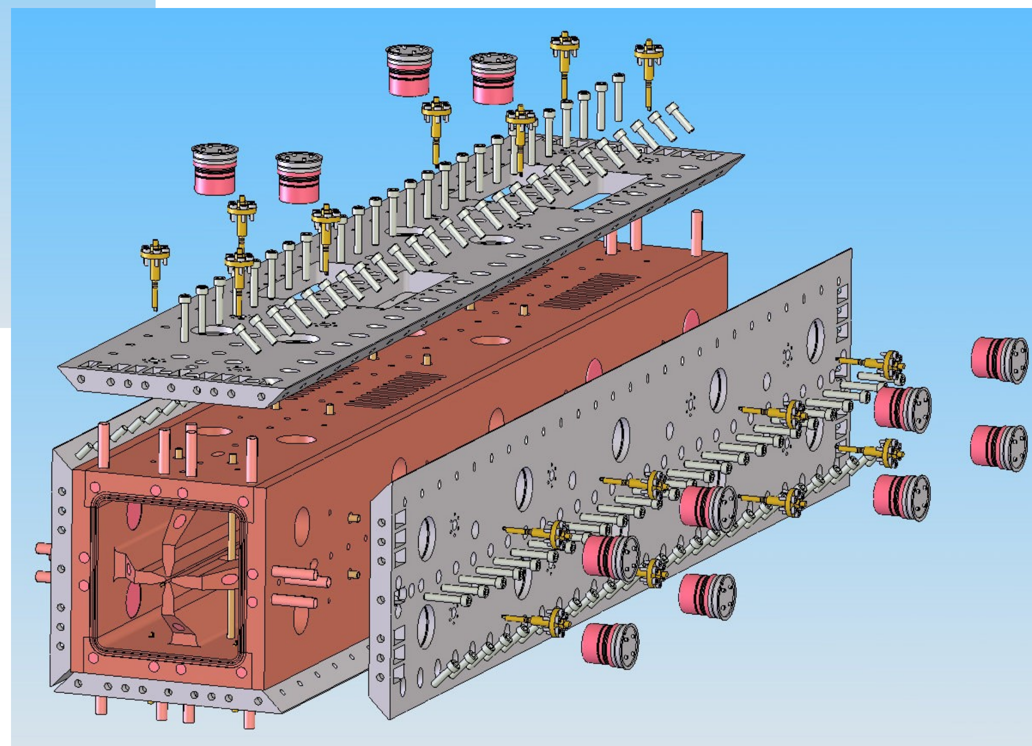
325 MHz RFQ Cross Section Engineering Analysis

162.5 MHz RFQ will use some of these techniques.



Each 133 cm modules has 24fixed tuners, 8 pumping ports.

Brazed copper inner cavity, with a bolted-on stainless steel exoskeleton



266 cm long, two modules

Cooling passages are rifle-bored in the copper substructure.

Two RFQ drive loops provided

Reduce RFQ Energy to 2.1 MeV?

Gains:

Below the neutron threshold in copper.   Copper is found in the RFQ and elsewhere

The TW deflectors produce a 19% larger angle

The beam power in the collimators is 84% less

The RFQ gets shorter, requiring less RF power

Stabilization of the RFQ mode structure gets simpler (cheaper, less power)

Loss:

The first SC must accept a β = 0.0669 velocity

Possibly more emittance growth in MEBT (although recent simulations do not show this)

Action Items

Do acceptance test of ion source at TRIUMF

Set up ion source test stand at LBNL, continue testing and characterization

Implement as much LEBT as possible, including LEBT chopper

Measure dynamic characteristics of LEBT chopping and beam neutralization

Agree to a set of RFQ parameters

Start engineering analysis of RF structure

Carry out detailed Microwave Studio analysis of structure stabilization, error tolerances

Summary

An ion source will be run and characterized at LBNL

A LEBT with 2 solenoids will be constructed and operated with an electrostatic chopper and diagnostics. (The dipole can come later.)

A fast LEBT chopper presents significant emittance issues after RFQ

RFQ frequency now frozen at 162.5 MHz. Good beam dynamics solution obtained

Select final RFQ output energy so engineering can proceed.

Backups

Issues for Possible 20 MHz LEBT chopper

20 MHz beam chopper with 10 MHz deflector: 2 zero-crossings per cycle

4 cm long chopper 75 electrical degrees of 10 MHz long

β = 0.0065 low for a TW chopper design

For square wave to sharpen edges of chop, next harmonic of 30 MHz is 225 electrical degrees long. Reducing individual longitudinal chopper electrodes reduces their electrical length, but the transverse spacing of the plates reduces the higher-frequency fields on axis.

Plates > 2 cm apart, shorter chopper will still have long effective length and more nonlinear fields.

Time average of RFQ output beam emittance is large

The RFQ phase acceptance $\pm\pi$. Any beam at the RFQ entrance will be accepted into one of the phase buckets.

Longer chop produces satellite bunches.

Shorter chop reduces current within one phase bucket.